The Principle of Digital Subtraction Angiography and Radiological Protection

K. OKAMOTO, J. ITO*, K. SAKAI, S. YOSHIMURA**

*Department of Radiology, Niigata University School of Medicine and **Niigata University Hospital, *Department of Radiology, Niigata University School of Dentistry*

Key words: fluoroscopically guided interventional procedure, digital subtraction angiography, radiation protection

Summary

Recent improvements in x-ray technology have greatly contributed to the advancement of diagnostic imaging. Fluoroscopically guided neurointerventional procedures with digital subtraction angiography (DSA) are being performed with increasing frequency as the treatment of choice for a variety of neurovascular diseases. Radiation-induced skin injuries can occur after extended fluoroscopic exposure times, and the injuries have recently been reported. In this article, measured radiation doses at the surface of Rando Phantom with Skin Dose Monitor, and estimated and measured entrance skin doses in patients underwent neurointerventional procedures are reported as well as means of reducing radiation doses absorbed by patients and personnel to avoid occurrence of radiation-induced injuries.

Introduction

More than one hundred years have passed from the discovery of x rays by Wilhelm C. Röntgen. The mysterious rays gave a light on many patients, but the rays produced many victims in the period, in which diagnostic as well as therapeutic radiology has made a rapid progress.

We have accumulated experience and knowledge of the x rays and radiation injuries through numerous clinical cases and unfortunate events. International Commission on Radiological Protection (ICRP) provides recommendations on all aspects on radiation protection. In its Publication 26 and 60 the ICRP issued its basic recommendations for the principles of radiation protection as follows: 1) *justification*, "no practice involving exposure shall be adopted unless its introduction produces a net benefit", 2) *optimization*, "all radiation exposures should be kept as low as reasonably achievable (ALARA), economic and social factors being taken into account", and 3) *limitation*, "the dose equivalent to individuals shall not exceed recommended dose limits for the appropriated circumstances". All radiological procedures need to satisfy these principles.

In the recent clinical settings, serious radiation injuries do not occur in routine diagnostic procedures. After the beginning of the 1990s, fluoroscopically guided interventional procedures have been increasingly used to treat various neurovascular diseases. A combination of the improvement of digital subtraction angiography (DSA) and the introduction of new devices including microcatheters and fine guidewires as well as coils and embolic materials facilitates the interventional treatment.

In many cases, longer periods of radiation exposure are required than the exposure times associated with diagnostic procedures. Serious radiation-induced skin injuries resulting from fluoroscopically guided interventional procedures have recently been reported [1-4]. It is im-

portant for physicians performing these procedures to know the accumulated radiation dose of patients during the procedures, and to make efforts to minimize the radiation exposure to patients in order to avoid occurrence of radiation injuries.

Radiation Measurement (Exposure and Equivalent Dose)

Radiation exposure is a measure of the concentration of free electrons produced in air by the x rays. 1 R (roentgen) is defined as quantity of x ray producing a charge of 2.58 x 10^{-4} C (coulombs) per kilogram air. That is 1 R = 2.58 x 10^{-4} C/kg. The quantity exposure is being replaced by the quantity air kerma. The unit of kerma is the gray (G), and 1 Gy of kerma is equivalent to 1 J (joule) of energy transferred to charged particles per kilogram of irradiated medium. For air, 1 Gy (100 cGy) of kerma is equivalent to 115 R of exposure; therefore, 1 cGy is approximately equal to 1 R[5].

The unit of absorbed dose is the gray, which is the same unit as for kerma, and 1 Gy of absorbed dose is equivalent to 1 J of energy absorbed by the medium per kilogram of absorbing medium.

Equivalent dose is a measure of the potential biological effect from different types of radiation. The unit of equivalent dose is the joule per kilogram, with the special name of sievert (Sv). Equivalent dose is the product of the average absorbed dose in a tissue or organ and its associated radiation weighting factor (W_R). For x rays, this value is equal to 1. Therefore, 1 Sv is equivalent to 1 Gy. For the purpose of discussing the potential effects of diagnostic x rays, there is no essential difference between an equivalent dose of 1 Sv and an absorbed dose of 1 Gy.

The Principle of Fluoroscopy and Digital Subtraction Angiography (DSA)

Fluoroscopes produce immediate and continuous images. Today, fluoroscopic machines employ an image intensifier and TV system. TV recording systems are usually employed to record the image. An image intensifier greatly improves image quality by amplifying x-ray beams, and converts an x-ray image into a light image that can be displayed on a TV monitor through an image processor. The contrast and brightness controls on the TV monitor must be properly adjusted prior to x-ray application. If the controls are inappropriate, excessive radiation doses are required in fluoroscopy. Brightness gain of the intensifier becomes less as screens age. Reduction can be as much as 10% per year[6]. As the image intensifier ages and loses efficiency, the automatic brightness control automatically increases the primary beam technique factors and exposure rates to keep an adequate light level to the camera. An image intensifier used more than five or six years should be exchanged for new one. The increases of radiation exposure result in an increase of doses to the patient and personnel.

Resolution of intensifiers is 4 line-pairs/mm for modern cesium iodine (CsI) intensifiers. The contrast and brightness of an image can be controlled by adjusting the peak kilovoltage (kVp) and the milliamperage (mA) of the x-ray tube. In fluoroscopy, typically both kVp and mA are adjusted automatically by the machine, but the kVp and mA also correlate the dose to the patient. In general, a relatively high kVp and a low mA are preferred[6]. Many image intensifiers have multiple field-size viewing (e.g., 7 inch, 9 inch, and 11 inch). The smaller the field size, the more magnified the image appears on the TV monitor. The entrance dose rate to the patient generally increases if magnification mode is used. The x-ray field can be defined manually by use of the collimators located just outside of the x-ray tube. Tight collimation is necessary for the control of image quality and radiation dose.

In DSA, the initial image from an angiographic sequence is stored in memory. The subsequent images are subtracted from this image and displayed as a continuous display on a video monitor. This enables a complete monitoring of the examination as it is in progress. The image information is also simultaneously stored on a digital disk at real-time rates[7].

Advances in digital technology, including DSA, have made it possible to acquire serial images at rates and quantities not possible with conventional film-changer and film-cassette technologies. Dose rates from digital imaging can be much greater than those from fluoroscopy (see the next Entrance skin dose measurements with a phantom).

Entrance Skin Dose Measurements with a Phantom

Surface doses were measured with a Skin Dose Monitor (model 104-101, MacMahone Medical Inc., San Diego, CA, USA) at the occiput and at the right temple of the head of Rando Phantom containing a human skeletal system (female type; height 163 cm, weight 54 kg). The x-ray device used was an automatic exposure-controlled fluoroscope (Angioskop D 33, Siemens, Erlangen, Germany) and a DSA system (Polydoros 80). The distance between x-ray tube and the image intensifier was 100 cm. The x-ray tube was placed under the table in a posteroanterior view examination, and placed right side of the phantom head in a lateral view examination. Available sizes of the image intensifier were 7, 9, and 11 inch.

The data were acquired three times for each size of the image intensifier in both posteroanterior and lateral planes. Table 1 summarizes the entrance skin doses associated with fluoroscopy in the continuous mode for 1 minute duration, table 2 with DSA (10 frames), and Table 3 with conventional angiography (10 exposures).

Entrance Skin Dose Calculation and Measurements in Clinical Cases

Among radiological records of 74 patients underwent neurointerventional procedures from September 1, 1998 to August 31, 1999, the most extended fluoroscopic exposure time required for embolization of a cerebral arteriovenous malformation was 102 minutes with 1113 frames of DSA, and 44 film exposures. For radiation dosimetry purposes, it was estimated that 80% was performed in the lateral plane and the remaining 20% of fluoroscopy was performed in the posteroanterior plane. If the acquired data with the Rando Phantom are applied to this patient with cerebral arteriovenous malformation assuming that the radiation beam constantly irradiates the same area and that there was no overlap between the posteroanterior and lateral planes, the maximum possible skin dose is estimated to be 3.2 Gy at the right temple.

We measured entrance skin doses in 12 patients underwent neurointerventional procedures from October 1, 1999 to February 29, 2000 with the Skin Dose Monitor. A sensor of the Skin Dose Monitor was placed on the right temple in nine patients in whom the lateral projection was mainly used, and was placed on the occiput in three patients in whom the posteroanterior projection was mainly performed. Measured skin doses ranged 383.8 mGy to 1918.6 mGy (1.9 Gy). The maximum dose was recorded at the occiput of a patient underwent

Table 1 **Entrance Skin Dose Measured on the head of Rando Phantom**

Fluoroscopy for 1 minute		
I.I. size	**Posteroanterior plane [75 kV, 2.2 mA]**	**Lateral plane (RL) [68 Kv, 1.8 mA]**
11 inch	17.4 (0.5) mGy	13.2 (0.2) mGy
9 inch	30.3 (0.8) mGy	20.8 (0.1) mGy
7 inch	47.0 (0.3) mGy	30.4 (0.1) mGy

I.I., image intensifier, technique factors are enclosed by brakets; numbers in parentheses are S.D.

Table 2 **Entrance Skin Dose Measured on the head of Rando Phantom**

DSA, 10 frames		
I.I. size	**Posteroanterior plane [70 kV, 420 mA, 62 msec]**	**Lateral plane (RL) [70 Kv, 555 mA, 21 msec]**
11 inch	16.7 (0.5) mGy	9.4 (0.0) mGy
9 inch	21.7 (0.1) mGy	19.0 (0.0) mGy
7 inch	24.3 (0.3) mGy	24.0 (0.0) mGy

I.I., image intensifier, technique factors are enclosed by brakets; DSA, digital subtraction angiography; numbers in parentheses are S.D.

transvenous coil embolization for dural arteriovenous fistula of the posterior fossa with 66.2 minutes of fluoroscopy using 9 inch image size of the image intensifier and 474 frames of DSA and 53 film exposures. In this patient, the estimated skin dose was calculated to be 2.4 Gy if it was estimated that 80% of fluoroscopy was performed in the posteroanterior plane and the remaining 20% was performed in the lateral plane. The measured dose (1.9 Gy) was 79.2% of the estimated dose. The measured skin dose was less than the estimated dose in every case, and the measured doses ranged from 32% to 81.5% of the estimated doses.

Entrance Skin Doses in a Head CT Examination

The entrance skin dose of the head of the Rando Phantom during a head CT examination was also measured with thermoluminescent dosimeters (TLD). A TLD was placed on the midline of the phantom forehead in the 5-mm-thick scan plane. Additional TLDs were placed on the midline at intervals of 5 mm away from the TLD in the scan plane along the body axis. The CT equipment used was Hitachi W-1000 (Hitachi Medical, Tokyo, Japan). A 5 mm-thick CT scan was performed with use of standard radiologic parameters of 120 kV, 175 mA, and 2.9 seconds. Measured entrance skin dose in the scan plane was 54.9 mGy, those at 5 mm and 10 mm away from the scan plane were 2.2 mGy and 1.3 mGy, respectively. TLDs placed more than 15 mm away from the TLD in the scan plane showed the same values to the back ground. Therefore, if contiguous CT sections are obtained, the cumulative entrance skin dose becomes 61.9 mGy (1.3 mGy + 2.2 mGy + 54.9 mGy + 2.2 mGy + 1.3 mGy). If pre- and postcontrast studies are performed, the dose becomes 123.8 mGy (61.9 mGy + 61.9 mGy). In our hospital, another CT scanner made by a different manufacturer is used for clinical practice. However, there is no significant difference between the measured entrance skin doses with these scanners using the same radiological parameters. The surface doses during axial scans and helical scans are the same if the scan parameters are identical. Therefore, the estimated entrance skin becomes 185.7 mGy (123.8 mGy + 61.9 mGy) if 3D-CT angiography with the same parameters is added to 5-mm thick pre- and postcontrast CT studies (usually entrance skin dose during 3D-CT angiography is lower than that of axial scans because a higher kV, a lower mAs, and a shorter scanning time are used in 3D-CT angiography). This value of 185.7 mGy is far less than that from the fluoroscopically guided neurointerventional procedures.

Table 3 **Entrance Skin Dose Measured on the head of Rando Phantom**

Conventional angiography, 10 exposures	
Posteroanterior plane [73 kV, 6.3 mA]	**Lateral plane (RL) [70 Kv, 5.6 mA]**
9.4 (0.0) mGy	7.6 (0.2) mGy

I.I., image intensifier, technique factors are enclosed by brakets; numbers in parentheses are S.D.

Discussion

In radiation protection, the ICRP has established three recommended standards, namely *justification*, *optimization*, and *limitation*. In practice of radiation protection, the guiding philosophy is ALARA (as low as reasonably achievable)[5].

However, review of the circumstances of many of the injuries revealed a lack of appreciation by the physicians performing interventional procedures, prior to observing the injury, of the magnitude of the skin dose that can result from the long exposure time that may be required by complex interventional procedures[2]. Doses from serial digital imaging can markedly increase both patient dose and the possibility of a severe radiation-induced injury. The estimated entrance skin dose at the right temple of our patient with cerebral arteriovenous malformation exceeded 3 Gy.

In addition, many patients undergo therapeutic procedures that require two or more sessions. Huda et Al reported the estimated maximum possible skin dose of 6.6 Gy for a patient, who underwent embolization of a left paraorbital arteriovenous malformation guided with a neurobiplane x-ray system in two sessions separated by 3 days[1]. In this case imaging included 110 minutes of fluoroscopy and 46 DSA acquisitions, and the patient reported a temporary epilation in the right occipital region of the

skull approximately five weeks later. The temporary epilation is reported to be produced after radiation doses of 3-5 Gy and is most severe in the second and third weeks [8].

Although the exit dose was measured to be about 1% of the entrance skin dose for the posteroanterior projection, the closest lens could receive a maximum entrance skin dose for the lateral projection [1]. The minimum dose required to produce a progressive cataract is about 2 Gy in a single exposure. The latent period between irradiation and the appearance of a lens opacity is dose related. The latency is about 8 years after exposure to a dose in the range of 2.5 to 6.5 Gy [9]. Therefore, our patient with calculated dose of 3.2 Gy at the right temple in the interventional procedure might have a possibility of developing cataract as a result of radiation exposure associated with embolization of a cerebral arteriovenous malformation.

Accurate estimation of entrance skin dose should be calculated from not only fluoroscopic exposure time and number of DSA frames, but also data on technical factors of x-ray system, exposure rates during fluoroscopy and exposure per frame during DSA, patient thickness, and system geometry [2]. An important assumption was made in the dose calculation that the x-ray beam was continually directed to the same region of the skull. However, the location and size of the irradiated area varied with the projection, which were not monitored during the procedures.

Therefore, actual entrance skin dose might be less than the calculated dose as in our cases. The accurate skin dose measurements can be obtained with use of thermoluminescent dosimeters, which allows dose measurement over a wide range with sufficient accuracy [3,4,10]. Transient alopecia developed after neurointerventional procedures is reported in two patients in an article, in each of whom the dose at the right temporal area was about 4.2 Gy [3]. Lately Skin Dose Monitor with a radiolucent sensor has become available for the real-time measurement of accumulated radiation dose at the site of application on a patient. The introduction of a radiation-monitoring system provides feedback to the operators regarding both the instantaneous and cumulative dose associated with the procedure, and may help reduce patient doses by increasing operator awareness of any high patient doses [1].

Current applications of digital fluoroscopy, especially high-dose-rate fluoroscopy (0.1 Gy/min), and DSA have increased the radiation load to the patients significantly. This of course increases proportionately the radiation exposure to the operator [11]. Operator equivalent doses are measured at various sites [3]. The maximum measured operator doses are 3.55 mSv at the left hand, 1.99 mSv at the left arm, 1.1 mSv at the neck out side of a thyroid protector, and 0.88 mSv at the glabella, respectively. According to the most recent ICRP recommendations regarding radiologic protection (ICRP Publication 60), the operator dose limit is 150 mSv/year for lens, 500 mSv/year in the skin. Calculations indicate that an operator performing 170 (150/0.88) or more neurointerventional procedures in a year has a potential risk of exceeding the dose limit for the eye, and 140 (500/3.55) or more procedures for the skin. In an operator who conducted the DSA in a patient, the doses at many sites were far higher than those in the examination of other patients. Transcarotid approach rather than the transfemoral approach was used because of tortuosity of the vessels in the case. The short distance between the x-ray source and the operator resulted in the high operator dose [3]. The radiation intensity decreases proportionately as the square of the distance from the x-ray tube. Although a small amount of radiation is emitted through the shielded x-ray tube housing (i.e., leakage), primary scatter emitted from the patient is the major source of hazard to personnel in fluoroscopy. Flexible protective clothing such as aprons, vests, skirts, and thyroid shields, can significantly reduce transmission of scattered radiation. The transmission through 0.5 mm of lead equivalent (typical lead equivalent thickness for aprons) is 3.2% at 100 kVp and 0.36% at 70 kVp [12]. The typical flexible material for protective clothing is lead-impregnated rubber. Special composite materials that may be lightweight and easier to wear are also available but usually more expensive [5]. Other types of shielding, including mobile barriers such as a floor-standing transparent barrier and a ceiling-suspended transparent barrier with a suspended drape, are available and fluoroscopic tables may be purchased with optional shielding and leaded drapes that protect personnel from patient scatter [5].

The operator should put on a heavy leaded

glove to protect his/her hand when it is exposed to the primary beam. All protective clothing items should be evaluated both at a acceptance for attenuation properties and integrity of the shielding and periodically for shielding integrity (i.e., to check for cracks or holes)[5]. Eyeglasses with side shields are available with or without prescription lenses for eye protection for personnel who need them. There is an argument against the necessity for wearing eyeglasses during interventional procedures. Radiation-induced cataracts, a deterministic response, exhibit a dose threshold to x rays of approximately 10 Gy because of the temporal distribution of the radiation. Essentially it is not possible for an angiographer to receive such a dose. The average neuroangiographer would have to work perhaps hundreds of years just to reach the dose threshold[11].

Typically, reducing patient dose also reduces dose to personnel. The duration of exposure of the individual is directly proportional to the doses to the patient and the operator. The most important and reliable, and easily achievable means is to keep beam-on time to an absolute minimum. It is the golden rule in practice of radiation protection and may be accomplished effectively through judicious use of the exposure switch to ensure that irradiation is occurring only when the fluoroscopist is actively viewing the image.

Use of a last-image hold feature can be helpful in reducing the overall beam-on time[5]. All new fluoroscopes should be purchased with this feature. Pulse-mode fluoroscopy is a technology that uses pulses of radiation, rather than a continuous beam, to produce fluoroscopic images. Pulsed fluoroscopy can reduce exposure times in procedures. In a continuous beam mode, images are obtained at frame rates of 30 frames per second, but a rate of 15 frames per second is usually enough for viewing images. Marked decrease of the skin dose of the patient is achievable if the rate is reduced from 30 frames per second to 15 frames per second or less[13]. Using frame rates and series durations that are as low as diagnostically acceptable in serial radiographic studies reduces the overall time of patient irradiation.

Thin metal plates called added filters are inserted in the x-ray tube housing below the exit window. In diagnostic radiology, the metal most commonly used is aluminum (Al) because of its low atomic number. It removes the lower-energy photons in the beam that would otherwise be absorbed by the skin of the patient and are useless in the formation of the image. The filter can reduce the radiation skin-dosage of the patient at the irradiated area[4,14]. Another type of filtration, the heavy-metal filter, has now been introduced into clinical use as a way to improve image contrast in procedures. Use of such a filter has several advantages. Heavy-metal filters tend to narrow the spread of energies, both high- and low-energy photons; removal of low-energy photons assists in reducing the patient's radiation dose, and the removal of higher-energy photons tend to reduce the amount of scatter. Heavy-metal filters employ material such as gadolinium (Gd) and holmium (Ho) among others[15].

In these ways, both patients and personnel receive ALARA radiation doses.

Radiation induced central nervous system sarcoma is an uncommon but well-recognized serious late complication which has occurred following radiotherapy. A few cases of radiation-induced gliomas have also been documented. In these cases, reported initial and cumulative tumor inducing doses of orthovoltage and megavoltage x-ray, and proton irradiation ranged from 20 to 100 Gy[16]. Such therapeutic radiation doses cannot be irradiated to patients undergoing to neurointerventional procedures. However, meningiomas induced by low dose extracranial irradiation for Tinea Capitis are reported with administration doses less than 8 Gy[16-18]. If multi-sessional neurointerventional procedures are performed in a patient, the cumulative skin dose may reach to the dose of 8 Gy. All the patients with radiation induced meningioma received scalp irradiation before the age of 10, and the meningiomas presented clinically more than 20 years after irradiation[17]. Postirradiation meningiomas have distinct characteristics as follows, 1) their location at the site of maximal irradiation; 2) features suggesting rapid growth and aggressive biological behavior; 3) higher proportion of multiple meningiomas; 4) increased number of histologically malignant meningiomas[18]. A higher local recurrence rate is also noted[16,18].

Although the carcinogenic risk to patients from the radiation associated with neurointerventional procedures is very low, and an estimated carcinogenic risk factor is about 10^{-1} Sv^{-1}

for acute radiation exposure [1], ALARA should be achieved by physicians performing the procedures.

Conclusions

Accompanying radiological technologists optimize image quality and establish the technological optimization using the best geometric configuration for fluoroscopic procedures (tight collimation and proper distances among the x-ray tube, patient, and image intensifier) for reducing patient dose and the hazard from scattered radiation.

However, only the physician can be responsible to the justification for exposure to radiation. If more serious complications occur in many patients underwent neurointerventional procedures, the justification will be lost and the interventional procedures will not be accepted as the treatment of choice for various neurovascular diseases.

Acknowledgment

We thank H. Hinata, B.Sc., T. Tanaka, R.T., E. Noguchi, R.T., and T. Oka, R.T. for their data acquisition, and Y. Ito, M.D., H. Abe, M.D. in Department of Neurosurgery, Brain Research Institute Niigata University for their cooperation.

References

1 Huda W, Peters KR: Radiation-induced temporary epilation after a neuroradiologically guided embolization procedure. Radiology 193: 642-644, 1994.
2 Shope TB: Radiation-induced skin injuries from fluoroscopy. RadioGraphics 16: 1195-1199, 1996.
3 Kuwayama N, Takaku A et Al: Radiation exposure in endovascular surgery of the head and neck. Am J Neuroradiol 15: 1801-1808, 1994.
4 Norbash AM, Busick D et Al: Techniques for reducing interventional neuroradiologic skin dose: Tube position rotation and supplemental beam filtration. Am J Neuroradiol 17: 41-49, 1996.
5 Brateman L: The AAPM/RSNA physics tutorial for residents, radiation safety considerations for diagnostic radiology personnel. RadioGraphics 19: 1037-1055, 1999.
6 Dowd SB: Fluoroscopy: viewing motion with x-ray. In: Thompson MA, Hall JD et Al (eds): Principles of imaging science and protection. W.B. Saunders, Philadelphia 1994: 361-376.
7 Ovitt TW, Newell II JD: Digital Subtraction Angiography: technology, equipment, and techniques. Radiologic Clinics of North America 23: 177-184, 1985.
8 United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR): Source, effects and risks of ionizing radiation: Report to the General Assembly. United Nations, New York 1988.
9 Hall EJ: Radiobiology for the radiologist. 4th ed. J. B. Lippincott, Philadelphia 1994: 379-384.
10 Bergeron P, Carier R et Al: Radiation doses to patients in neurointerventional procedures. Am J Neuroradiol 15: 1809-1812, 1994.
11 Bushong SC: Hazards evaluation of neuroangiographic procedures: Am J Neuroradiol 15: 1813-1816, 1994.
12 Yaffe MJ, Mawdsley GE et Al: Composite materials for x-ray protection. Health Phys 60: 661-664, 1991.
13 Aufrichtig R, Xue P et Al: Perceptual comparison of pulsed and continuous fluoroscopy. Med Phys 21: 245-256, 1994.
14 Hattaway MP: Improving image quality. In: Thompson MA, Hall JD et Al (eds): Principles of imaging science and protection. W.B. Saunders, Philadelphia 1994: 309-340.
15 Thompson MA: Factors affecting the x-ray spectrum. In: Thompson MA, Hall JD et Al (eds): Principles of imaging science and protection. W.B. Saunders, Philadelphia 1994: 221-234.
16 Kumar PP, Good RR et Al: Radiation-induced neoplasms of the brain. Cancer 19: 1274-1282, 1987.
17 Gomori JM, Shaked A: Radiation induced meningiomas. Neuroradiology 23: 211-212, 1982.
18 Soffer D, Pittaluga S et Al: Intracranial meningiomas following low-dose irradiation to the head. J Neurosurg 59: 1048-1053, 1983.

Kouichirou Okamoto, M.D.
Department of Radiology
Niigata University School of Medicine
Niigata, 951-8510 Japan